Novel Manufacturing Platform for Scale up Production of Miniaturized Parts

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The increased industrial interest in miniaturization of "mechatronic" products is driving the demand for manufacturing platforms that can address the requirements for scale up production of parts that incorporate different scales functional features. The paper reports the development of such manufacturing platform, which integrates the capabilities of complementary component technologies, in particular 3D printing, 3D optical scanning, data processing, micro-milling and laser micro-machining, and thus to produce products with meso and micro features with required accuracy, repeatability, reproducibility and surface integrity. The necessary level of functional integration of the modules is achieved through the development of a specialized workholding device and automated workpiece’s setting up routines, which allow different machining configurations and strategies to be implemented for increased processing efficiency. Case studies are presented to demonstrate the capability of the proposed micro manufacturing platform.

1. Introduction

The demand for product miniaturization, increased precision and reduced cost of mechatronic devices has been increasing continuously across a number of application areas such as micro-electromechanical systems, micro-sensor systems and microelectronics.1 Various manufacturing processes such as milling, forming, additive manufacturing and laser processing are widely employed for their production. They provide reliable and at the same time scalable solutions at relatively lower manufacturing costs.1 However, when these manufacturing processes are individually employed they often fail to deliver products that meet all requirements concerning accuracy, geometrical complexity, surface integrity and manufacturing costs due to their intrinsic technological limitations. For example, such critical limitations can be associated with the shape of the cutting tools in milling that introduce constrains in regards to the complexity of shapes which can be fabricated at micro scale. At the same time additive manufacturing processes can produce complex shapes but they build parts with relatively poor surface quality due to the “stair-step” effect. Laser machining is another processing alternative however it is usually viable only when small volumes of material have to be removed due to relatively low removal rates.

Thus, the cost effective manufacturing of miniaturised parts that incorporate different scale functional features necessitate complementary processing technologies to be integrated into manufacturing platforms and thus to overcome the limitations of single processing routes. Such platforms are also called hybrid because they combine complementary processes to form fabrication solutions which exploits the advantages of a component technology in order to overcome shortcomings of another.1

The most recent efforts of researchers on hybrid manufacturing at micro and nano scale are focused on combining different manufacturing processes with the objectives to improve surface integrity, products’ accuracy and processing efficiency and also to reduce tool wear and production time.3 For example, a combination of additive manufacturing and milling can significantly reduce manufacturing time and cost by employing additive manufacturing for the near-net shape fabrication of parts while their high quality and accuracy is achieved by employing milling as a finishing step.4

Another approach to improve the capabilities of manufacturing solutions is to combine conventional with non-conventional processes such as laser micro machining. Such manufacturing solutions offer non-contact machining, ability to process wide range of materials and complex free-form (3D)
surfaces that incorporate functional features with wide range of sizes and capabilities for in-situ selective surface characteristics customization. For example, a combination of micro-milling and laser structuring was reported to produce complex biotechnology products with feature sizes smaller than the cutting tool diameter without compromising machining time. This manufacturing platform benefits from the complementary capabilities of its component technologies for a higher removal rates and higher machining resolution, respectively.

The carried out literature review revealed that most hybrid manufacturing processes are product specific, which makes their fabrication capabilities highly dependent on products’ specific technical requirements and also vulnerable to design changes even within their respective application areas. This is exemplified by the fact that their process designs are mainly focused on extending particular capabilities of well-established conventional manufacturing processes such as milling. Usually they aim to address product-specific machining requirements rather than the development of a new manufacturing solution for a diverse range of application areas. Furthermore, the analysis of such manufacturing platforms also shows that they can be implemented in different configurations and thus to accommodate specific manufacturing requirements, namely to reduce production time by combining concurrently complementary processes or they represent sequential combinations of processes to increase product accuracy, repeatability and reproducibility (ARR).

The designs requiring a sequential combination of manufacturing processes in a single machine set-up could be very challenging due to some dissimilar machining requirements of the integrated processes such as the clamping of the workpieces, the necessary machining workspace, the physical characteristics of the process and also safety considerations. For example, a combination of additive manufacturing with milling have to accommodate in a single set-up different manufacturing requirements, in particular well controlled environment to build parts in layer by layer fashion from powder while the follow-up subtractive machining introduces specific fixturing requirements to resists the cutting forces and also to protect machined parts from occasional spatter during the additive manufacturing process. At the same time, the productivity of such hybrid solutions is greatly reduced due to the sequential integration of the processes that allows only one manufacturing technology to be active at a time. In contrast, concurrent process integrations lead to higher production rates because the processes can be executed simultaneously.

A critical requirement in designing hybrid manufacturing platforms is the need for precise repositioning of the workpiece in different machine set-ups as this has a direct impact on the products’ ARR. A precise workpiece positioning is especially important for manufacturing platforms that integrate non-conventional machining processes such as laser micro machining, because the lateral machining area defined by the laser beam diameter at the focal plane is often in the range of a few tens of micrometres while the depth of cut from a few microns down to sub-microns. Even though workpiece repositioning issues have been recognized in a number of investigations, further research is needed in order to develop workholding devices for multiple processing setups as an integral part of hybrid manufacturing platforms. The objective in designing such platforms is to allow scale-up production of miniaturised parts with high ARR that at the same time incorporate meso and micro scale functional features.

The research in this paper is focused on the development of novel integration solutions for hybrid manufacturing platforms that can provide the required level of flexibility, accuracy and robustness to combine laser micro machining with different complimentary processes for the scale-up production of miniaturised parts. The next section first introduces the component technologies of a reconfigurable laser micro machining system for hybrid manufacturing platforms. A workholding device that can be utilised to realise different machining configurations and strategies is proposed and then its capabilities for accurate, repeatable and reproducible positioning of workpieces are studied. In addition, the paper presents automated workpiece’s setting up routines that reduce the operators’ efforts and the necessary time for aligning workpieces in laser micro machining set-ups. Finally, two case studies are presented that demonstrate the capabilities of hybrid manufacturing platforms that integrate laser micromachining modules for scale-up production of miniaturized parts with meso and micro functional features.

2. Integration component technologies for hybrid manufacturing platforms

Laser ablation is a complementary technology to additive manufacturing and micro machining processes and their integrations offer promising solutions for the fabrication of miniaturized parts for various application areas. However, most laser micro-machining platforms are still built for specific application areas, which limits their compatibility with other processes. Therefore, reconfigurable laser micro-machining platforms that improve the compatibility of laser micro processing with other complementary manufacturing technologies, is a critical requirement for the successful integration of this technology in hybrid manufacturing platforms.

2.1 Reconfigurable laser micro-machining system

Laser micromachining platforms should have sufficient flexibility to realise different processing operations, e.g. polishing and structuring of parts with varying sizes, multi-scale features and geometrical complexity, in order to address specific requirements in regards to ARR, surface integrity and processing efficiency. To achieve this they have to integrate a range of component technologies that include: i) cost effective
short and ultra-short pulsed laser sources with high repetition rate and different laser spot characteristics; ii) optical axes (beam deflectors) for realising beam movements with high dynamics and accuracy; iii) exchangeable focusing telecentric lenses to vary the size of the machining area and beam spot; iv) a device (Z module) for dynamic beam spatial modulation (focusing) for high speed processing; v) high precision 3-axis stages for processing surfaces with lateral dimensions bigger than the working volume defined by the optical axes and the Z module; vi) rotary axes (stages) for processing complex parts and also to realize different manufacturing configurations; vii) a workholding device with the necessary modularity for process integration; viii) measurement probes for parts’ inspection and also to implement automated process setting up routines; ix) CNC system with software tools for counteracting dynamic effects of optical axes. The focus of this research is on two of these component technologies, especially the workholding device and automated process setting up routines.

2.2 Modular workholding device

The integration of laser micro-machining modules into hybrid manufacturing platforms with high ARR requirements\(^1\) is highly dependent on precise alignment of workpieces in each of the integrated processing setups. At the same time workpiece alignment methods can be both very time consuming and not sufficiently accurate due to the necessity to perform a registration of the workpieces’ datums in each set-up by highly experience operators.\(^9\) Furthermore, workpiece imperfections or defects can be a major cause for errors due to the use of different datums, alignment devices and procedures in each processing modules of the hybrid manufacturing platforms.\(^9\) Therefore, workholding devices have to fulfil the following critical requirements:

- High ARR;
- Compatibility with different manufacturing processes;
- Capability to realize different machining strategies;
- Robust and compact design;
- Simple and fast integration in different manufacturing systems.

Fig.1 depicts a schematic representation of a modular workholding device, which addresses all requirements listed above. Its components are commercially available and can be easily integrated in different manufacturing systems such as milling and EDM machines and laser machining platforms.\(^11\)

The modularity of the proposed workholding device is ensured by installing macro receivers (chucks) in each of the integrated processing systems that allows a common pallet to be used for each manufacturing setup. Thus, the workpieces can be directly mounted onto the interface plate of the pallet and subsequently carried throughout the entire sequence of processing stages. In this way the same Workpiece Coordinate System (WCS) can be preserved in regards to the receiver in each machining setup of the hybrid manufacturing platforms as shown in Figure 2.

![Fig. 1 Schematic representation of a modular workholding device](image1)

Fig. 1 Schematic representation of a modular workholding device (1 – Workpiece; 2- Interface plate; 3- Pallet; 4 – Drawbar; 5 - Macro receiver (chuck))

The proposed workholding device also possesses the capability to realize different manufacturing setups with the use of modular fixturing designs. For example, a laser micro-machining system that integrates fixturing designs incorporating one or two pallet systems (one as workholding device) can be used to realise different machining configurations as depicted in Figure 3.

The positioning repeatability of the workholding device is better than 1 µm\(^11\), and thus such modular fixturing designs can provide highly precise positioning of workpieces on multiple setups in hybrid manufacturing platforms.
2.3 Automated workpiece’s setting up routine

Conventional workpieces’ settings up techniques for laser machining rely on experienced machine operators and are very time consuming. Such manual procedures include:

- Precise referencing of the surfaces that will undergo machining in regards to the focal plane of the laser beam;
- Referencing of the lateral position of the workpiece in regards to the field of view of the focusing lens.

Figure 4 exemplifies the procedure that has to be executed to reference manually WCS in regards to the Machine Coordinate System (MCS). The vertical alignment of the workpiece (along z axis) is performed by machining a grid of lines with different z settings to find the focal plane and thus the MCS origin. The lateral referencing of the workpiece is achieved by identifying manually alignment marks or existing parts’ features with a high resolution camera. Then, the readings of the machine controller are used to calculate the $d_x$ and $d_y$ displacements of WCS, and MCS in relation to MCS, and MCS, respectively and angles $\Theta_x$ and $\Theta_y$ that give the rotation of the workpiece relative to the x and y axes of the laser machine. The derived values of $d_x$, $d_y$ and $\Theta$ are then entered into the laser system controller to complete the referencing procedure. The main drawbacks of this procedure are its uncertainty that is highly dependent on operators’ experience and the resolution of the camera employed, and also the time necessary to execute it.

To reduce the uncertainty and the time associated with the manual setting up of laser micro-machining modules in hybrid manufacturing platforms, an automated workpiece’s setting up routine is proposed. The routine employs a single alignment device, namely a confocal probe that only has to be brought in a close proximity to the alignment marks and then the routine can be executed automatically by the machine controller.

Furthermore, the use of this automated solution offers some very appealing advantages such as non-contact detection of the workpieces’ machining surfaces, a higher precision and much lower uncertainty compared with the manual procedure due to the high-resolution positioning capabilities of the probe. The execution of the proposed workpiece’s setting up routine (shown in Figure 5) includes a number of automated commands, in particular:

- Scanning of an alignment cross from the start position (Point 0) along the x axis of the laser machine to identify Point 1 (intersection point of MCS with WCS);
- Scanning of the alignment cross from the start position (Point 0) along the y axis of the laser machine to identify Point 2 (intersection point of MCS with WCS);
- Repositioning of the optical probe to Point 3;
- Scanning of the alignment cross from Point 3 along the x axis of the laser machine to identify Point 4 (intersection point of MCS with WCS);
- Scanning of the alignment cross from Point 3 along the y axis of the laser machine to identify Point 5 (intersection point of MCS with WCS);
- Scanning along the z axis at Point 6 to find MCS, at which WCS is at the focal plane of the laser beam.

Based on the measurement results (x and y coordinates of the intersection points of MCS with WCS, Points 1, 2, 4 and 5) the orientation angles ($\Theta_x$ and $\Theta_y$) of WCS in relation to MCS and the origin of WCS in MCS (Point 6) can be calculated by employing the following derived equations:

$$\Theta_x = \tan^{-1}\left(\frac{y_2-y_1}{x_2-x_1}\right); \quad \Theta_y = \tan^{-1}\left(\frac{x_2-x_1}{y_2-y_1}\right);$$

$$x_6 = x_2 - \left(\sin \Theta_x (\cos \Theta_x) (x_2-x_1) - (y_2-y_1) \tan \Theta_x\right);$$

$$y_6 = y_2 - \left(\cos \Theta_x (\cos \Theta_y) (x_2-x_1) - (y_2-y_1) \tan \Theta_x\right).$$

After the completion of this automated routine, MCS, $x$, $y$, $z$, $\Theta_x$, $\Theta_y$ are recorded by the laser machine controller and then used to carry out the workpiece machining.
3. Case studies

The capabilities of the proposed hardware and software tools to increase the compatibility of the laser micro-machining process with other manufacturing processes is demonstrated with two different case studies, in particular when 3D printing and mechanical milling are employed as preceding manufacturing steps to laser machining.

3.1 Integration with 3D printing

3.1.1 Process design and experimental validation

A hybrid manufacturing platform that combines 3D printing, in particular the Digital Metals (DM) technology, with laser micro-machining was implemented for scale-up production of highly customized and complex parts. The specific technical requirements that the platform had to satisfy were to fabricate Stainless Steel (SS) 316 parts with dimensional accuracy better than 10 µm and surface roughness, Ra, better than 1 µm. A test part was designed that included different size geometrical shapes in order to assess objectively the capability of this hybrid manufacturing platform to meet the technical requirements of the considered range of parts. Figure 6 presents the CAD model of the test part together with the complete sequence of processing steps used to produce the part.

The first module of the platform is a DM 3D printing system to produce near net shape SS 316 parts. The 3D printing step includes a 3D model preparation, printing of “green” parts and then sintering. The module has the capabilities to produce SS 316 parts with surface roughness, Ra, down to 3 µm and dimensional accuracy of down to 50 µm. Following the near net shape fabrication step, the parts are fixed on the interface plate of a common pallet that provides fast and precise repositioning of the part in the subsequent modules of the manufacturing platform. The parts on the pallets were scanned with a 3D optical measurement system, in particular employing the Focus Variation technology with measurement uncertainty better than 0.5 µm, to obtain a digital representation of the near net shape parts. Then, a specially developed software tool was used to compare the digital representations of the near net shape parts with their nominal (CAD) models and create “rest volume” models for further laser micro processing. With the use of the automated alignment routine the 3D printed parts were aligned with their corresponding “rest volumes” models and laser micro machining was performed to achieve the necessary level of dimensional accuracy and surface quality. Following the laser processing step, the parts were again inspected with the 3D optical measurement module in order to verify whether the parts conformed to their technical specifications. If the parts were not of required quality, they underwent further laser processing until they met their technical requirements in regards to dimensional accuracy and surface integrity.

To investigate the capabilities of the modular workholding device for accurate and repeatable repositioning of the parts on different processing modules of this hybrid manufacturing platform, two square 0.5x0.5 mm fields on the 3D scanned model of the part were selected for laser polishing. Figure 7 shows these two fields on the model of a 3D printed part together with their nominal positions. The polishing of the two fields was performed in two separate laser processing steps and the pallet with the part was inspected in the 3D optical measurement module after each polishing operation. The inspections were used to assess both the positioning accuracy and repeatability of the workholding device. In particular, the inspection of the part after laser polishing the first field was used to evaluates the positioning accuracy of the workholding device while the second inspection to assess its the positioning repeatability.

3.1.2 Results and discussion

Figure 8 shows the positions on the part of the two laser polished square fields. It is evident that in both polishing operations the positioning error does not exceed 10 µm. This demonstrates the capability of the workholding device to interface different modules of the hybrid manufacturing platform with accuracy and repeatability better than 10 µm. Furthermore, the implementation of a common pallet for transferring parts between the processing steps of the manufacturing platform also eliminates the necessity to register the parts in each of the modules and thus significantly reduces the overall fabrication time and efforts.

Finally, Figure 9a shows a typical surface topography of the 3d printed SS 316 parts surface while Figure 9b depicts the resulting surface integrity improvements after laser polishing. The optimised laser settings used to carry out the polishing operation on the 3D printed SS316 part are provided in Table 1. The surface roughness, Sa, achieved after laser polishing the two square fields was in the range from 0.25 to 0.4 µm while the initial Sa values were ~ 3 µm. This represents more than 80% surface roughness improvement and was much better than the required Ra values of better than 1 µm.
Fig. 6 The test part together with the processing steps used for its fabrication

Fig. 7 The positions of the two square fields on the scanned model of the 3D printed part (all dimensions are in mm)

Fig. 8 Measurements of the two laser polished fields carried out with the 3D inspection module

Fig. 9 Surface roughness (a) 3D printed SS 316 part and (b) after laser polishing
3.2 Integration with mechanical milling

3.2.1 Process design and experimental validation

The hybrid manufacturing platform reported in this section includes a combination of mechanical milling and laser structuring in order to achieve a scale-up fabrication of high precision parts with the required level of ARR. A passive waveguide filter was selected as a test part due to its complex geometry that included micro- and meso-scale functional features. Figure 10 presents the CAD model of the test part together with its processing steps.

In the first step of the process, a brass plate with 70x70x1 mm dimensions was fixed onto the interface plate of a common pallet. Then, the pallet was placed in a CNC machining centre to produce the meso-scale features of the part, in particular to cut off a 2x2 array of parts with overall 30x30 mm dimensions and machine an alignment mark (a cross) for follow-up processing. Then, the pallet with the part was placed in the laser micro-machining module, where the waveguide of the filter was structured. This was carried out by employing the proposed automated workpiece setting up routine and the alignment cross produced in the preceding step. In addition, a specially developed software tool for counteracting dynamic effects of optical axes was used to increase ARR of the laser micro structuring operations and also to reduce substantially the machining time.

In order to investigate the capabilities of the proposed automated workpiece setting up routine for reducing product manufacturing time and increasing machining accuracy and repeatability, two experimental trials were performed:

-Trial 1: machining of the waveguide structure by utilizing the automated workpiece setting up routine;

-Trial 2: machining of the waveguide structure by utilizing a conventional workpiece setting up routine (manual identification of the alignment mark with a camera).

3.2.2 Results and discussion

Figure 12 shows the laser structured waveguide of the passive waveguide filter together with the alignment cross both for Trial 1 and Trial 2. It can be clearly seen that the alignment of the waveguide in Trial 1 is with a higher accuracy than that in Trial 2. In particular, the rotational error of the structure in regards to the alignment mark in Trial 1 is less than 0.01˚ while in Trial 2 exceeds 1˚. The reason for the lower positional accuracy in Trial 2 is the fact that the conventional setting up procedure is affected by the high uncertainty associated with the operator experience in identifying manually the alignment mark with a camera. At the same time, the alignment procedure in Trial 1 is fully automated and takes much less time, in particular less than 2 minutes in comparison to more than 12 minutes in Trial 2. Thus, the automated workpiece setting up routine can significantly increase the throughput of the proposed manufacturing platform while delivering a higher ARR.

The structuring of the waveguide was carried out by employing the optical axes of the laser micro machining module. The process settings used to perform the laser structuring operation are provided in Table 1.

Table 1 Laser processing parameters from the two case studies

<table>
<thead>
<tr>
<th>Material</th>
<th>3D printed part</th>
<th>Waveguide filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS316</td>
<td>Brass</td>
<td></td>
</tr>
<tr>
<td>Average Power [W]</td>
<td>40</td>
<td>4.2</td>
</tr>
<tr>
<td>Frequency [kHz]</td>
<td>70</td>
<td>500</td>
</tr>
<tr>
<td>Pulse duration [μm]</td>
<td>220 ns</td>
<td>310 fs</td>
</tr>
<tr>
<td>Beam Diameter [μm]</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Scanning Speed [m/s]</td>
<td>0.21</td>
<td>2</td>
</tr>
<tr>
<td>Layers</td>
<td>1</td>
<td>15</td>
</tr>
</tbody>
</table>

Fig. 11 The CAD model of the waveguide filter with its processing steps
The ARR results are summarised in Table 2 where the features produced by laser machining in Trial 1 are compared with their nominal dimensions. These results demonstrate clearly that the dimensional accuracy of the features is better than 10 µm. It is worth stressing that this high accuracy was achieved with the used of optical axes at scanning speed of 2 m/s that reduces substantially the machining time, in particular from 391s when the mechanical stage was used to carry out the machining to 102s without sacrificing the structuring accuracy. These results shows clearly the advantages that the use of the developed software tools for counteracting dynamic effects of optical axes can offer.

Table 2 Results from the laser machining trials of the waveguide filter

<table>
<thead>
<tr>
<th>Feature</th>
<th>1 and 6</th>
<th>2 and 5</th>
<th>3 and 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal width [µm]</td>
<td>100</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Average width [µm]</td>
<td>100.8</td>
<td>153.1</td>
<td>148.8</td>
</tr>
<tr>
<td>Deviation [µm]</td>
<td>+0.8</td>
<td>+3.1</td>
<td>-1.2</td>
</tr>
<tr>
<td>Nominal length [µm]</td>
<td>175</td>
<td>290</td>
<td>340</td>
</tr>
<tr>
<td>Average length [µm]</td>
<td>175.1</td>
<td>296.5</td>
<td>346.3</td>
</tr>
<tr>
<td>Deviation [µm]</td>
<td>+0.1</td>
<td>+6.5</td>
<td>+6.3</td>
</tr>
</tbody>
</table>

Fig.12 Laser structured waveguides in Trial 1 and Trial 2

4. Conclusions

This paper presents novel software and hardware integration tools for hybrid manufacturing platforms that increase the compatibility of the laser micro-machining process with other fabrication processes. The following conclusions could be drawn from this research:

- Conventional alignment of workpieces in hybrid manufacturing platforms does provide the required ARR for serial production of miniaturized parts and also it is very time-consuming. The reasons for this are workpiece imperfections, especially when 3D printed parts have to be machined, and the manual registrations of WCSs in different machining setups by machine operators.
- The application of modular workholding devices can deliver highly accurate and repeatable repositioning of parts in hybrid manufacturing platforms with multiple machining setups and also capabilities to realize different machining configurations and strategies.
- Automated setting-up routines for laser processing modules in hybrid manufacturing platforms can greatly increase their throughput while maintaining a higher level of ARR in the fabrication of complex miniaturized parts.

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